# Air-Sea Interaction in High Winds and the Role of Spray

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Award Number: N0001400MP20031
http://www.crrel.usace.army.mil/

## LONG-TERM GOALS

The goal is to investigate, theoretically and through analyzing existing data, the role that sea spray plays in transferring heat, moisture, and momentum across the air-sea interface, especially in high winds. Ultimately, we hope to develop simple parameterizations for these air-sea fluxes for use in large-scale models, especially those simulating tropical and extra-tropical storms.

## OBJECTIVES

The ultimate goal of this work is to understand the physics and, thus, how to parameterize the air-sea fluxes of momentum and sensible and latent heat at all wind speeds. Since the COARE bulk flux parameterization (Fairall et al., 1996) is successful at winds speeds of 10 m/s or less, I focus on higher wind speeds, where sea spray is present and is a likely transfer agent. Succinctly, the first objective is to learn how to partition the air-sea fluxes between interfacial and spray contributions. The sum of the net sensible and latent heat fluxes via all routes is called the total enthalpy flux. Because this total enthalpy flux, rather than the individual sensible and latent heat fluxes, provides the energy for tropical storms, the second objective is to develop a parameterization for the air-sea heat fluxes—including spray effects—that is suitable for use in large-scale air-sea interaction models. The third objective focuses on air-sea momentum exchange in high winds and on how spray and other surface disruptions alter this exchange.

## APPROACH

This work is theoretical and analytical; there has been no experimental component. Microphysical theory establishes how rapidly spray droplets can exchange heat and moisture in a given environment. Theoretical considerations also predict how the sea spray generation function should depend on wind speed. The analytical part involves developing parameterizations for the various processes under consideration by simplifying model results or by synthesizing various data sets and observations reported in the literature. Checking the parameterizations being developed against available data is also another aspect of what I call analytical work.

Theory and microphysical modeling suggest we can estimate the total (i.e., both interfacial and spray) air-sea latent ($H_{L,T}$) and sensible ($H_{s,T}$) heat fluxes as (e.g., Andreas and DeCosmo, 1999)

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE **SEP 2000** | 2. REPORT TYPE | 3. DATES COVERED **00-00-2000 to 00-00-2000** |
| 4. TITLE AND SUBTITLE **Air-Sea Interaction in High Winds and the Role of Spray** | | 5a. CONTRACT NUMBER |
| | | 5b. GRANT NUMBER |
| | | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | | 5d. PROJECT NUMBER |
| | | 5e. TASK NUMBER |
| | | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U. S. Army Cold Regions Research and Engineering Laboratory,,72 Lyme Road,,Hanover,NH,03755-** | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | 10. SPONSOR/MONITOR’S ACRONYM(S) |
| | | 11. SPONSOR/MONITOR’S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT **unclassified** | b. ABSTRACT **unclassified** | c. THIS PAGE **unclassified** | **Same as Report (SAR)** | **8** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

$$H_{L,T} = H_L + \alpha Q_L , \qquad (1)$$

$$H_{s,T} = H_s + \beta Q_S - (\alpha - \gamma) Q_L . \qquad (2)$$

Here, $H_L$ and $H_s$ are the so-called interfacial fluxes that I estimate with the COARE bulk flux algorithm (Fairall et al., 1996), and $Q_L$ and $Q_S$ are nominal spray latent and sensible heat fluxes predicted by Andreas's (1992) microphysical model. $\alpha$, $\beta$, and $\gamma$ are small, nonnegative coefficients obtained by tuning (1) and (2) with data.

**WORK COMPLETED**

To evaluate $\alpha$, $\beta$, and $\gamma$, I have been using the HEXOS (for Humidity Exchange over the Sea experiment) measurements of the sensible and latent heat fluxes (DeCosmo, 1991; DeCosmo et al., 1996). The magnitudes of the nominal spray fluxes, $Q_L$ and $Q_S$, in (1) and (2) depend on the sea spray generation function I use. I have tuned (1) and (2) to the HEXOS data for two candidate spray generation functions—Andreas (1992) and Andreas (1998). With the former, $\alpha = 4.3$, $\beta = 6.5$, and $\gamma = 3.8$; with the latter, $\alpha = 9.8$, $\beta = 15.0$, and $\gamma = 9.3$. The differences in these values reflect the persistent uncertainty in the magnitude and wind speed dependence of the spray generation function.

In collaboration with Kerry Emanuel at MIT, I investigated what my spray model says about the net air-sea enthalpy flux. From (1) and (2), that net enthalpy flux is

$$Q_{e,net} = H_{s,T} + H_{L,T} = (H_s + H_L) + (\beta Q_S + \gamma Q_L) . \qquad (3)$$

The first two terms on the right-hand side of (3) give the interfacial enthalpy flux,

$$Q_{e,int} = H_s + H_L , \qquad (4)$$

which is modeled fairly well with a bulk-aerodynamic formulation, such as the COARE algorithm (Fairall et al., 1996). The last two terms in (3) give the enthalpy flux associated with spray processes,

$$Q_{e,sp} = \beta Q_S + \gamma Q_L . \qquad (5)$$

Note that the terms in (5) derive strictly from the sensible heat exchange, as modeled by (2). Few have recognized this fact and, thus, have generally ignored this important route for air-sea enthalpy exchange. Consequently, no large-scale air-sea interaction model is currently parameterizing the spray contribution to the air-sea heat flux with the proper physical basis. Recently, however, Andreas and Emanuel (1999, 2000a, 2000b) have begun incorporating spray effects in Emanuel's (1986, 1995) axi-symmetric tropical cyclone model, using (5) as a guide.

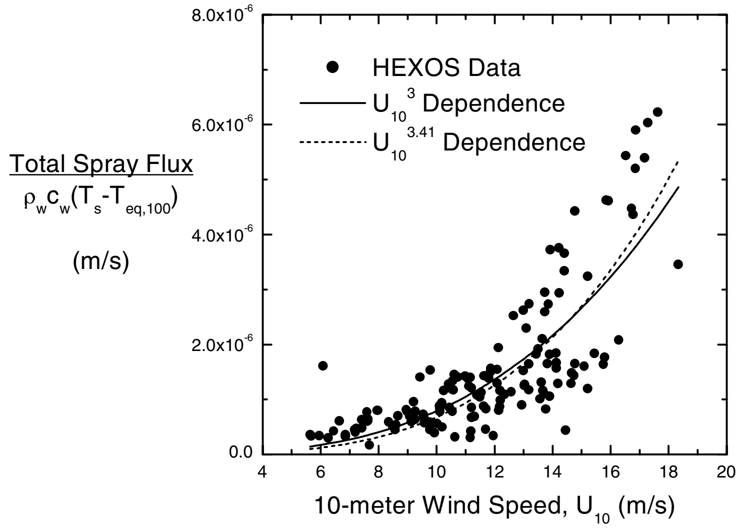


***Figure 1. Parameterization for the total spray enthalpy flux. The HEXOS data come from Andreas and DeCosmo's (1999) partitioning of the HEXOS turbulent heat fluxes into interfacial and spray contributions. The figure shows two alternatives for the wind dependence of the spray enthalpy flux. One goes as $U_{10}^{3.41}$ to reflect the increase in whitecap coverage with wind speed (Monahan and Ó Muircheartaigh, 1980). The other goes as the cube of $U_{10}$ and is the function that Andreas and Emanuel (2000a) use. Also, $\rho_w$ is the density of seawater; $c_w$, the specific heat of seawater; $T_s$, the sea surface temperature; and $T_{eq,100}$, the equilibrium temperature of 100-µm spray droplets (e.g., Andreas, 1995, 1996).***

**RESULTS**

Figure 1 shows the parameterization for the spray enthalpy flux in (5) that Andreas and Emanuel (2000a, 2000b) developed. Although spray droplets with radii between 1 and 500 µm are important in transferring heat and moisture across the air-sea interface, Andreas (1992) showed that droplets with radii near 100 µm carry most of the sensible heat. To make the parameterization simple, we thus assume that these 100-µm droplets dominate the spray heat exchange and, therefore, parameterize $Q_{e,sp}$ in terms of these droplets alone. This explains the $T_{eq,100}$ (the equilibrium temperature of spray droplets of 100-µm radius) in Figure 1.

With expressions for the spray generation functions, it is relatively easy to use droplet conservation arguments to estimate an upper bound on spray's ability to transfer momentum across the air-sea interface. The concept is straightforward. Spray droplets are ejected into the air at a 'known' rate (i.e., the spray generation function) and with little or no horizontal velocity. Since the wind accelerates them rapidly to the local wind speed, they extract momentum from the wind. When these droplets then crash back into the sea, they transfer this momentum to the sea in the form of a surface stress. By assuming that all droplets produced fall back into the sea, I have estimated spray-drag coefficients from the Andreas (1992) and Andreas (1998) spray generation functions. For the wind speed range of the

Andreas (1992, 1998) spray generation functions, these spray-drag coefficients are 2-3 orders of magnitude less than the usual interfacial drag coefficient modeled with a Charnock relation (e.g., Fairall et al., 1996) or with Large and Pond's (1981) relation (Andreas and Emanuel, 2000b). But they increase more rapidly with wind speed than the interfacial drag coefficient. Consequently, indications are that spray drag may be an important momentum sink in hurricane-strength winds. In fact, to produce realistic storm development in their tropical cyclone simulations, Andreas and Emanuel (2000a) found it necessary to postulate a heuristic spray-drag function that is an order-of-magnitude larger than the estimated spray drag. Clearly, we have a long way to go in understanding air-sea momentum transfer in high winds when the sea surface is severely disrupted.

## IMPACT/APPLICATIONS

In finding that sea spray can accomplish a net enthalpy exchange across the air-sea interface, we have identified an unappreciated source of energy that can influence the intensity of tropical and extra-tropical storms. Fairall et al (1994) were the first to investigate how sea spray could affect the development of the marine boundary layer in a tropical cyclone and confirmed that the spray can redistribute heat between the temperature and humidity fields. By identifying how and how much the spray can affect the net air-sea enthalpy flux, we suggest that not only does the spray redistribute heat in the atmosphere, it can actually transfer energy across the air-sea interface and thereby affect storm intensity.

Not all have accepted this conclusion or have been able to support it with models, however. For example, modeling reported by Kepert et al. (1999), Wang et al. (1999, 2000), and Uang (1999) reiterates the conclusion by Fairall et al. (1994)—that spray can affect the temperature and humidity profiles in the marine boundary layer in storm conditions. But these models show minimal effects of spray processes on maximum storm intensity. Perrie et al. (2000), on the other hand, report roughly a 20% spray effect in their simulations of extra-tropical storms in the North Atlantic.

Most of the papers I just cited have appeared in the last two years and, therefore, reflect the current vitality of the work in this area and its perceived importance. In fact, the diversity of opinions as to which processes are important in high winds provided some of the impetus for ONR's new departmental research initiative on Coupled Boundary Layers and Air-Sea Transfer (CBLAST).

## TRANSITIONS

I contributed to the ONR 'whitepaper' that lays out the scientific issues that CBLAST should address, and I participated in the Airlie workshop that reviewed these issues. I have also been invited to lecture on sea spray at Woods Hole Oceanographic Institution and at the National Center for Atmospheric Research during a workshop concerning the air-sea interface that was sponsored by NCAR's Geophysical Turbulence Program.

The most direct transitions of this research, however, are through my collaborations with Kerry Emanuel at MIT, Wade McGillis at WHOI, and Will Perrie at Bedford Institute. These collaborations involve developing parameterizations for air-sea transfer in high winds that acknowledge the role played by sea spray and other surface disruptions.

## RELATED PROJECTS

The Division of Atmospheric Sciences at the National Science Foundation is currently funding me for a three-year project to study “Air-Sea Fluxes at High Wind Speeds with Application to Tropical Cyclone Intensity Prediction.” I am collaborating in this work with Wade McGillis and Jim Edson of WHOI, Tetsu Hara and Isaac Ginis of the University of Rhode Island, and Kerry Emanuel of MIT. I also have leveraged my ONR funding by collaborating on spray research with scientists outside CRREL who are funded by projects at their own institutions. For example, the publications listed below document collaborations with Ed Monahan at the University of Connecticut, Janice DeCosmo at the University of Washington, Martin Pattison at MindFlash Technologies, and Stephen Belcher at the University of Reading.

Finally, I am a member of the PhD. thesis advisory committee for Magdalena Anguelova in the College of Marine Studies at the University of Delaware. She is working on a thesis topic complementary to my own research, “Sea-Salt Aerosols: Their Generation and Role in Climate Systems.”

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